Different Methods in Building Envelope Energy Retrofit

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Abstract

With about 40% of energy consumption in U.S.A in 2011 consumed by Residential and Commercial sectors, different energy retrofit measures that lead to reduction in energy consumption for these sectors can result in a significant change in total energy consumption nationwide. Therefore, it is important to study the existing energy retrofit methods and investigate how effective these methods can be. These measures can be categorized into three main groups, including energy retrofit and improvement of the building envelope, mechanical, and electrical systems. This paper focuses mainly on different methods of building envelope energy retrofit. Examples of such methods include installation of exterior insulation such as rigid foam to wall or roof, installation of cool/warm roof, reducing air infiltration, changing window properties such as SHGC, application of PCM and Aerogel in different envelope components, and adding overhangs. The required data for this study are obtained from experimental and numerical studies available in the literature. Moreover, a computer model is developed using BEopt to study and compare the effectiveness of single and multiple retrofit methods in a residential building.

Keywords: Energy analysis, opaque envelope retrofit, exterior insulation, air infiltration, Residential and Commercial Buildings

Introduction

About 40% of energy consumption in U.S.A in 2011 has been by residential and commercial sectors. The resources that provide this energy include petroleum, natural gas, coal, and renewable energy that supply 16%, 75%, less than 1%, and 8% of the required energy, respectively (EIA, 2015). Based on the 2009 U.S. data, space conditioning, domestic hot water, and refrigerators have consumed, respectively, about 48%, 17%, and 5% in residential sector. The remaining 30% is consumed by appliances, electronics, and lighting. Energy consumption due to space conditioning varies depending on climate zones and age of home, because besides HVAC system, envelope systems are also responsible for the level of energy consumed for space conditioning. For example, about 25% to 35% of energy for space conditioning is wasted due to inefficient window systems (Oldfield et al. 2015). This is approximately equivalent to 6% of the total energy consumption of the nation. Energy consumption of residential buildings due to space conditioning is approximately 38% and 55% for Marine and Very Cold climate zones, respectively. Residential buildings constructed before 1940 use about 54% of the energy for space conditioning, while consumption is about 43% for houses built from 2000 to 2009. This shows how important and effective energy retrofit of building envelope of existing deficient residential and commercial buildings could be. Different energy retrofit measures can be considered in three main retrofit categories of building envelope, mechanical, and electrical systems. This paper is focused on the first category and mainly discusses different methods of building envelope energy retrofit that could be carried out on opaque and transparent components of existing buildings such as improving wall insulation or enhancing thermal performance of window systems. This paper also compares effectiveness of different energy retrofit methods based on available information in the literature.

Literature Review

In developed countries, the share of energy consumption of residential and commercial buildings is between 20% and 40% of total energy consumption (Pe´rez-Lombard et al., 2007). Energy consumed by residential buildings accounts for 22% of the total energy consumed annually in the U.S. In residential building sector, 42% of energy consumption is due to heating and cooling loads, while 36% is due to heat gain and losses, which is affected by building envelope. Most homes built before 1980 in the U.S. have either no insulation or at most up to R-11. Based on the data provided by the U.S. census, about 60% of existing homes fall in that category (Cooperman et al. 2011).

Energy retrofit can be simply categorized into conventional and deep energy retrofit. In conventional energy retrofit, usually simple and fast methods are used and different systems are considered separately (Zhai et al. 2011). For deep energy retrofit, however, a whole-building retrofit approach is usually considered. In order to decide on energy retrofit measures and options, it is useful to perform an energy audit beforehand. Accordingly, ASHRAE suggests three levels of energy audit for commercial buildings. In order to conduct a deep energy retrofit, it is required to do Level III analysis. Level I, which is also called simple audit, includes review of utility bills and walk-through the building. In Level II, detailed analysis of energy use for base loads, seasonal variation, and effective energy cost for different systems such as “Building Envelope, Lighting, Heating, Ventilation, and Air Conditioning (HVAC), Domestic Hot Water (DHW), Plug Loads, and Compressed Air and Process Uses (for manufacturing, service, or processing facilities)” are studied (microgrid-solar, 2010).

Conventional retrofit measures

Different insulation materials are available for energy retrofit of a building. The thermal conductivity of the conventional insulation materials ranges between 0.023 and 0.068 W/m-K. Depending on the energy retrofit method, a variety of materials can be used in different components of a building. For example, in a study with two different target objectives of cost-optimal and net-zero energy retrofit of a building, adding insulation to the exterior wall, roof and floor, and replacing windows are considered viable energy retrofit scenarios. For the former, Ferreira et al. (2014) used EPS in wall retrofit and XPS for roof and floor retrofits. The PVC frame and double glazed window were also considered as part of the window replacement in these retrofit scenarios (Ferreira et al. 2014). One of the easy methods to increase the R-value of a wall system is to add an exterior foam insulation. For example, R-etro system that includes expanded polystyrene (EPS), plastic clips, galvanized steel starting track, and fasteners provides an additional R-18 insulation to a wall system, which is good enough for avoiding condensation behind the new layer in cold climate zones. The retrofit design would also need providing a ¼" gap behind the foam and the existing wall by placing base plates in the ties, which can be used as a drainage system for any intruded water behind the insulation layer. Finally, it is easy to install different types of siding over the foam layer (Holladay, 2009).

Energy retrofit of building envelope systems is not limited to adding insulation material. For example, in the "overcoat" energy retrofit approach applicable to roofs, the retrofit consists of adding insulation and providing a space above it for ventilation. There are also less conventional materials used in energy retrofit of historical buildings. Pertosa et al. (2014) studied the application of 10 cm insulation layers made of reed over a cement plaster finish. There is also innovative tile system used in this study that has 15% higher reflectance but has the same visual appearance (Pertosa et al., 2014). There are series of reports based on studies conducted by Pacific Northwest National Laboratory for the Department of Energy that investigate different energy retrofit methods. In a study on office buildings (PNNL, 2011), the energy retrofit options for building envelope include adding exterior window film, exterior window shading and light shelves, wall and roof insulation, vestibule, installing cool roof, and replacing windows. Other methods used in other studies conducted by this research institute include installing low solar gain window films, adding continuous air barrier to exterior walls, installing high R-value roll-up receiving door, and adding window overhangs (PNNL, 2013). Depending on the building location, existing envelope systems, climate zone, etc., the energy retrofit might be focused on different components.

New retrofit measures

There are research programs such as EASEE (Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-story, multi-owner residential buildings) devoted to finding innovative and preferably modular solutions for energy retrofit of existing residential buildings. Two prototype prefabricated shapeable retrofitting panel systems were proposed by this group including a single layer XPS with surface finishing and composite EPS panel coated on both sides with textile reinforced mortar (TRM) (Masera et al., 2014). These thermal insulation products can be applied on both external and internal surfaces, but the software models developed by TRNSYS show that using external insulation has 8% better energy performance, while the internal thermal insulation leads to 50% less investment cost and lower payback period (Kolaitis et al., 2013). Retrofit of building envelope can include façade retrofit. For example, one study discusses the use of multi-functional energy efficient façade system (http://www.meefs-retrofitting.eu) for residential buildings in cold climate regions (Paiho et al. 2015). Another type of façade system for energy retrofit is called Active Solar Thermal Façades (ASTFs), which can function as both a building envelope and solar collector component. Zhang et al. (2015) classified different ASTFs based on different methods, which shows that the ASTFs can be used as part of walls, windows, balcony, sunshield, or roof (Zhang et al., 2015).

While most innovative systems have been developed for wall retrofit, there are also a few approaches specific to roofs, one being "cool roof", which basically reflects the sunlight. This requires the surface to have high reflectance and thermal emittance, which is more useful for warm climates as it helps to absorb less heat (Levinson, 2009). Also, there are other alternatives such as Cool-Green roof. A research that uses Helichrysum Italicum plant for the green roof shows that it reflects about 44% of the solar radiation, which is about 4% more than a conventional concrete roof. It also reduces the number of the overheating hours in summer by 98% (Pisello et al., 2015).

Beside R-value, the concept of thermal inertia is also important. The difference between thermal inertia and thermal insulation is that the thermal inertia slows down the changes in temperature by absorbing the thermal energy for later use (release), while the thermal insulation slows down the heat transfer without storing the thermal energy. As a result, the temperature changes within the materials with thermal inertia are more significant. Smart materials such as phase change materials (PCMs) have thermal inertia and can be used for this purpose. The PCM is activated when the temperature reaches a certain level (typically between 23 and 26^{o} C), which means the PCM undergoes a phase transition by absorbing the heat. Phase transition could be from solid-solid, solid-gas, solid-liquid, or liquid-gas. The opposite phase transition occurs when the ambient temperature reaches the set point that is typically the night temperature. These materials can be used in walls, floors, and ceilings with operating temperature range of 20 to 35^{o} C (Casini, 2014). There are different types of PCMs with different latent heat and fusion point that are presented in Table 2.

Application of PCMs can be in two categories of micro- or macro- encapsulation, where the latter can be in the form of tubes, spheres, panels as containers, while in the former, polymer films are used as the container, and the diameter of these particles are less than 1 mm. They can be mixed with building products such as plaster, screed, concrete, gypsum, acrylic paints and wood products such as MDF and OSB (Casini, 2014). Typical building applications of this material include the following: adding Micronal PCM to plaster, gypsum boards, or plasterboards; integration within counter ceiling using prepackaged panels or bags, applying under the floor finish such as under the radiant floors; applying plaster or panel over the exterior side of the walls or roofs; applying on Trombe walls or solar greenhouses as screeds or panels to increase heat gain; and applying inside insulating glass.

An example of more innovative exterior retrofit system is external thermal insulation composite system (ETICS). The final finish over the added insulation layer can be made of other innovative materials such as plasters containing phase change material (PCM). In a research study in Italy (Ascione et al., 2014), a 3 cm wallboard was installed on the inner face of the wall containing PCM with melting point of 27ºC, and plaster containing PCM with melting point of 32ºC was applied on the exterior of an educational building. The results show that using these materials accompanied by replacing windows with low-e windows and new roof insulation materials can lead to up to 38% reduction in energy consumption of this building. Application of PCM wallboard is investigated in another study using a mathematical model that is available in EnergyPlus. The benefit of applying two layers of PCM plaster with different melting point is that individual layers can be activated in either summer or winter, which has resulted in a maximum impact of about 6% decrease in annual energy consumption (Ascione et al., 2014). However, it is observed that using microencapsulated PCM in construction materials such as concrete can decrease the compressive strength by 25% although it increases the latent heat by 35% (Narain et al., 2015).

Nanotechnology that helps making materials on the size scale of between 1 and 100 nanometer (nm) can be used for insulation applications as well. The thermal conductivity of the materials manipulated based on this technology can be about 0.004 W/mk. As one of these materials, Aerogel is a "solid nanoporous material with ultra-low density obtained by the dehydration of a gel by replacing liquid component with a gaseous one" (Casini, 2014), which can be obtained from different sources such as silicon, aluminum, chromium, tin, or carbon, but the most used is silica-based. Table 1 compares the properties of silica aerogel with glass. There are some products in the form of aerogel insulation mats that can be applied as underfloor and enhance the thermal properties of floors. There are also some panels with thermal conductivity of 0.013 W/mk that can be applied on the wall outer face. There are more options for interior walls such as rolls, semi-rigid panels, and pre-coupled gypsum boards. The latter consists of aerogel base felt coupled with gypsum active-air ® slab. These materials are still about 8-10 times more expensive compared with more conventional insulation materials (Casini, 2014). Energy modeling and analysis using Designbuilder showed that adding aerogel and replacing windows resulted in reducing energy loss through walls, uninsulated attic, windows and doors, and uninsulated ground by 35%, 25%, 25%, and 15%, respectively (Filate, 2014). Also, replacing cement plaster finishing material with 5 cm SLENTITE aerogel insulation board from BASF chemical company with thermal conductivity of 16 mW/(m.k) led to 71% reduction in energy loss through walls (Filate, 2014). Moreover, flooring panels consisting of ThermablokSP aerogel insulation board covered by rigid Magnesium Silicate that is a breathable, impact resistant, and thermally efficient material were used in this project. The total U-factor for the final retrofitted slab turned out to be 0.42 W/(m^2.K) (Filate, 2014).

Double-skin façade is another new energy retrofit method. The second layer is basically an additional façade over the existing façade that is transparent. The space between these two layers acts as an insulation layer that is heated up by solar radiation, and it can be ventilated if over-heated (Kim et al., 2014). Ma et al. (2012) also studied the state-of-the-art in energy retrofit of existing buildings and summarized key findings of multiple studies. The major methods observed in these studies include infiltration reduction, installing green roof, windows upgrading; using insulated reflective barriers, ceiling insulation, foundation insulation, roof insulation, air sealing and replacement of doors, and wall retrofits including replacing the cladding, adding exterior insulation, and installing house wrap over the exterior walls (Ma et al., 2012). Table 3 summarizes different energy retrofit methods that are reviewed in this paper and also the methods used in multiple case studies are summarized in Table 4.

Table 1. Comparison of the properties of silica aerogel with glass (Adopted from Casini, 2014)

Properties	Silica Aerogel	Glass
Bulk Density (kg/m^3)	5-200	2300
Internal surface area (m^2/g)	500-800	0.1
Refractive index at 632.8 nm	1.002-1.046	1.514-1.644
Light transmission at 632.8 nm	90%	99%
Thermal expansion coefficient at 20-80 ^{0}C (1/C)	2×10^{-6}	10×10^{6}
Thermal Conductivity at 25^{o}C (W/mK)	0.016-0.03	1.2
Sound speed in the medium (m/s)	70-1300	5000-6000
Acoustic impedance (Kg/m^2/s)	10^4	10^7
Electrical resistivity (Ωcm)	1×10^{18}	1×10^{15}
Dielectric constant 3-40 GHz	1008-227	40-675

Table 2. Different types of PCMs and their latent heat and fusion points (Adopted from Casini, 2014)

Material	Fusion temperature (^{o}C)	Latent Heat (kJ/kg)
Paraffin	6-76	170-269
Non paraffin	8-127	86-259
Fatty acids	17-102	146-242
Salt hydrates	14-117	68-296
Eutectics	15-82	95-218
Water	0	333

Table 3. Summary of the energy retrofit methods applied on the building envelope

Reference	The objective, building type, or the location of the study	Proposed retrofit measures	Saving determination method	Major results
Ojczyk	-	Exterior Thermal & Moisture Management System (ETMMS)	-	Decrease in ice damn formation and energy consumption
PNNL, 2011	Office Building	Exterior window film, exterior window shading, add wall insulation, roof insulation, and cool roof	-	Decrease in energy consumption
Pertosa et al.	Historical building	Application of insulation layer made of reed and innovative tile system	EnergyPlus model	Decrease in energy consumption
Masera et al.	Development of innovative systems	Single layer XPS with surface finish & composite EPS panel coated on both sides with textile reinforced mortar		
Kolaitis et al.		Thermal insulation composite panels	TRNSYS model	Better energy performance by 5%
Paiho et al.	Cold climate region of Finland and Russia	Application of two different multifunctional energy efficient façade system (Meefs) including Advanced Passive Solar Collector & Ventilation Unit Technological Unit (APSC&VU TU) and Advanced Solar Protection & Energy Absorption Technological Unit (ASP&EA TU) that work based on thermal storage and phase change material.	EnergyPlus model	
Zhang et al.	Classification of different ASTFs	Application of Active Solar Thermal Façade (ASTFs) as a building envelope component.	-	-
Pisello et al.	A residential building in Italy	Application of cool-green roof	-	Reduction in overheating hours by 98%
PNNL, 2013	School	Adding exterior insulating finish system (EIFS), replacing windows, rigid insulation on roof, and slab insulation	-	-
Evola and Margani	Apartment in Italy	Application of external thermal insulation composite system (ETICS) containing stone wool and building integrated PV (BIPV)	DesignBuilder model	Decrease in heat loss through walls by 85%
Ascione et al., 2014		Application of PCM as a plaster over the ETICS, replacing windows, new roof insulation		Reduction in energy consumption by 38%
Ascione et al., 2014		Application of PCM wallboard	EnergyPlus	Reduction in annual energy consumption by 6%
Boarin et al.	Historical building	Application of innovative tile system with higher reflectance rate		
Casini et al.	Materials and systems containing PCM and aerogel	Application of different products containing nano material such as aerogel. These products include aerogel underfloor mats, panels, and pre-coupled gypsum boards with aerogel. Application of Micronal PCM to plaster, Trombe walls, and etc.		
Filate et al.	Office building	Application of Nanogel® Aerogel insulation plaster, ThermablokSP board, and SLENTIT aerogel insulation board.	-	71% reduction in energy loss through walls
Kim et al.	-	Application of double-skin façade		

Table 4. Summary of the energy retrofit methods and their results in different case studies

Case Study	Envelope Retrofit Methods	Notes
Kosny et al.	high R-value exterior foam sheathing, triple-glazed windows passive solar heating from glazed sunspaces	three liters of heating fuel consumption per square meter per year after the energy retrofit
Morelli et al.	Using aerogel-stone wool mixture and vacuum insulated panels on walls Improving windows thermal properties	68% of energy saving after applying multiple retrofit systems including mechanical measures
German et al.	addition of R-13 dense-pack cellulose in wall cavity R-12 polyiso over the slab R-38 polyiso over the roof deck Triple-pane glazing	40% of energy saving after applying multiple retrofit systems including mechanical measures
Harrington and Carmichael	Using windows consisting of using suspended coated film and gas fill addition of reflective barriers behind radiators	32% of energy saving after applying multiple retrofit systems including mechanical measures
Hagerman	Improving air tightness high density cellulose and EPS added to the existing wall cavity	It was aimed for annual heating and cooling energy consumption of less than or equal to 4.75 kBtu/sf/yr
Aste and Del Pero	replacing the glazing system with argon filled double pane glass installing shading system and installing dynamic double skin façade installing ventilated façade consisting of an air gap behind the stone façade installing stone façade to work as thermal mass and glass wool as insulation	40% of energy saving after applying multiple retrofit systems including mechanical measures and solar panels.
Home on the Range	addition of exterior insulation over concrete block walls replacing the windows with low-e glazing system The exterior walls and roof were also painted a light color	Ended up with energy consumption of 46 kBtu/sf/yr after applying multiple retrofit systems including mechanical measures
Beardmore Building	adding extensive insulation to the exterior walls adding R-50 insulation in roof cavities add insulated low-e glazing system in the interior high solar reflectance material converting the roof to a cool roof	Ended up with energy consumption of 32 kBtu/sf/yr after applying multiple retrofit systems including mechanical measures
Aventine	EPA cool roof was installed	Ended up with energy consumption of 23 kBtu/sf/yr after applying multiple retrofit systems including mechanical and electrical measures
Alliance for Sustainable Colorado	a Mylar film was applied on the interior of curtain walls to reflect up to 60% of the heat during sunny days and reduce the internal heat loss in the winter	Ended up with energy consumption of 42 kBtu/sf/yr after applying multiple retrofit systems including mechanical and electrical measures
200 Market building	includes addition of 2 inches Polyisocynurate insulation with a white asphalt cap on the roof translucent cloth shades were used on the single pane window to reduce heat gain and infiltration	After both envelope and mechanical retrofit methods the energy saving is about 30%
Rocky Mountain Institute (UCLA)	using high-performance ultra-clear glazing adding horizontal shading configuration Adding R-15 batt insulation behind the masonry-clad brick	After both envelope and mechanical retrofit methods the energy saving was estimated to be 457,353 kWh per year
Rocky Mountain Institute (Stanford)	adding lightweight external sunshades	After both envelope and mechanical retrofit methods the energy saving was estimated to be 654,500 kWh per year
Rocky Mountain Institute (DMW)	Using double layer façade	After applying both envelope and mechanical retrofit measures annual energy use reduction is estimated to be 3,712 MBtu
Chang et al.	Adding R-10 spray foam over masonry walls, R-35 to roof, and cool roof	Other measures including mechanical and electrical were also used

Numerical investigation of different envelope retrofit methods

In this section, the effect of some energy retrofit measures on building envelope systems that were summarized in the previous section will be studied in order to quantify the influence of each method and compare their performances in different climate regions. In order to study the effect of different retrofit scenarios, a computer model is used and the results are compared with a benchmark house. The B10 Benchmark house in BEopt is used for this purpose (BEopt, 2016). All retrofit scenarios studied in this report are with regards to the building envelope energy performance improvement, including but not limited to application of exterior insulation, window film, roof insulation, advanced façade system, PCM materials, materials with higher reflectance, and materials containing aerogel. Several studies have considered benchmarks or reference houses with different properties. The floor area of houses built in the north-east between 1990 and 2000 ranges between 2105 ft^2 and 2435 ft^2, with typical site-built homes having 2.5 bathroom, 3 bedroom, full or partial basement, wood framing, vinyl siding, and 2 stories (U.S. Department of Commerce, 2014). The building properties related to the building envelope of the benchmark house in BEopt are presented in Table 5. Full basement is not included in the square footage; however, it has the same area as each of the two stories.

Table 5. The building envelope properties of the benchmark house defined in BEopt

Component/System	Properties	R-value ($h.ft^2.R/Btu$)	Cost ($\$/ft^2$)	Lifetime (Years)
Wall	R13 Fiberglass batt, 2×4, 16 in O.C. Framing Factor = 0.25	11.4	2.54	
Wall Sheathing	OSB		1.29	
Exterior Finish	Vinyl, Light Solar Absorptivity = 0.3	0.6	2.67	30
Unfinished Attic	Ceiling R-30 Cellulose Vented, Insulation thickness = 8.55 in Framing Factor = 0.07	31.3	1.42	
Roof Material	Asphalt Shingles, Medium Color = medium Absorptivity = 0.85 Emissivity = 0.91		1.78	30
Slab	Uninsulated			
Carpet	80% Carpet	2.08		
	0.5 in Drywall		0.65	
Exterior Wall Mass/Partition Wall Mass/Ceiling Mass	Sensible Capacity (Btu/F.ft^2) = 0.42			
	15%			
Window to Wall Ratio (B, F, L, R)	Perimeter/Area Ratio = 1.41			
Windows	Medium-Gain and Low-E Non-metal Frame Double-Pane and Argon-Fill	2.86	22.4	30
				30
Door Area/material	20 ft^2 Fiberglass - Swinging		14	

From the summary of various building envelope energy retrofit methods reviewed in this report, eight different retrofit scenarios listed in Table 6 are considered in this simulation study.

Table 6. Different energy retrofit methods used for computer modeling

No.	Energy Retrofit Method	Required change in computer model	No.	Energy Retrofit Method	Required change in computer model
1	Exterior insulation	Change in wall R-value by adding exterior insulation	4	Roof insulation	Change in roof R-value
1-1	Thermal insulation composite panel		5	Slab insulation	Change in slab R-value
2	Exterior window film	Change in window properties	6	PCM as plaster or wallboard	Change in thermal mass properties
3	Cool roof	Change in roof reflectance properties	7	Components containing or coated by aerogel	Change in wall and slab R-value
3-1	Tiles with higher reflectance		8	Decreasing air leakage	Change in air leakage properties

The analysis results of all the retrofit methods presented in Table 6 are explained in this section. Figure 1 through Figure 8 are obtained directly from BEopt and contain useful data that need to be interpreted to evaluate the impact of single and multiple energy retrofit methods. There are both electricity and gas as main energy resources for this building, therefore the energy consumption outputs are categorized into two types based on the energy source. For example, Figure 1 shows the required energy for Hot Water and Heating as provided by Gas (G) while other energy consumption components based on Electricity (E). The locations considered in this study are assumed to be in cold climate region, therefore, the heating load is the dominant energy consumption source. Some of the source energy consumption components do not change between different retrofit methods such as Lights, Large (Lg) Appliances, and Misc. The vertical axis shows the source energy consumption (vs. site energy consumption) in Million BTU per year, and the horizontal axis shows different retrofit cases. However, show the annualized energy related cost (AERC) versus the source energy saving. It should be noted that in BEopt the energy related cost includes both energy bill and loan cost (based on 30 years) that means the construction costs are also considered. All retrofit cases in this section are compared with the benchmark house in Table 7. The difference in initial construction cost and energy saving percentage compared with benchmark house is presented.

Adding exterior insulation

The first energy retrofit scenario studied is the effect of adding exterior insulation. Adding exterior insulation should increase the R-value of the wall system and decrease both heating and cooling loads by slowing down the heat flow through conduction to and from the interior space. Different scenarios are considered for exterior insulation, including R-5 XPS, R-10 XPS, R-15 XPS, R-6 Polyiso, and R-12 Polyiso, where all options include a layer of OSB. In the discussion that follows, the scenarios are referred to as Point and the benchmark house is shown as User-defined option in all figures. Figure 1 shows the results, where Points 1 through 5 refer to R-5 XPS, R-10 XPS, R-15 XPS, R-6 Polyiso, and R-12 Polyiso, respectively. It can be observed that R-15 XPS (Point 3) led to the lowest energy consumption, followed by R-12 Polyiso, R-10 XPS, R-6 Polyiso, and R-5 XPS. Table 7 summarizes the output in terms of construction cost and energy consumption. It can be observed that construction cost can increase up to $3,200 and energy saving would be up to 10.8%.

Increasing SHGC of windows

The next energy retrofit method is adding a layer of window film that changes the solar heat gain coefficient (SHGC). In general, in cold climate regions where the heating load is more dominant, it is more desirable to have larger SHGC in order to reduce energy consumption. The low, medium, and high solar heat gain coefficient (SHGC) values considered are 0.3, 0.44, and 0.53, respectively. Figure 2 shows the energy analysis results. It can be observed that there is no significant change in the annual energy consumption. The energy consumption for the 0.3, 0.44, and 0.53 values of SHGC corresponds to Point 2, User-defined point, and Point 1, respectively. The magnitude of these effects also depends on the window area and these percentages could be higher or lower in other cases with different window areas. Table 7 summarizes the energy consumption and construction cost. It can be observed that energy saving of about 0.1% compared with benchmark house is insignificant.

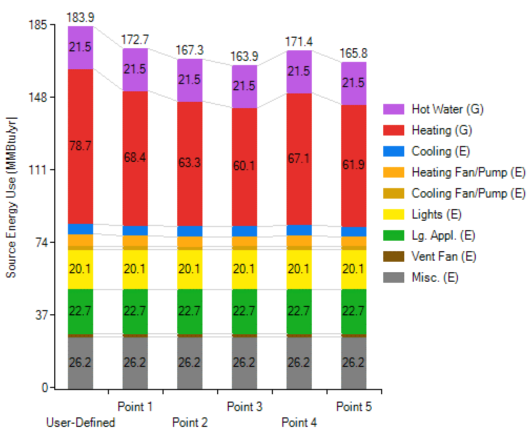

Figure 1. Comparison between different exterior insulation scenarios in terms of energy consumption

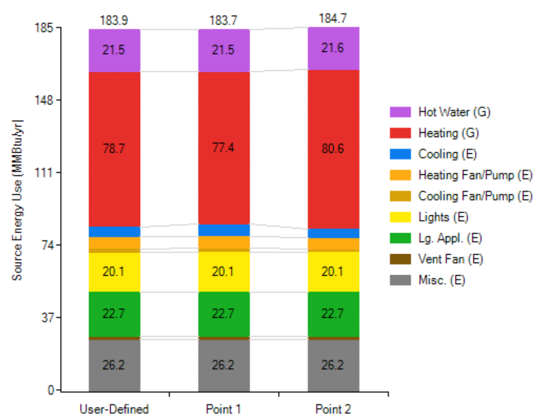

Figure 2. Comparison between the energy consumption for different glazing systems with different SHGC

Adding roof insulation

The next energy retrofit method is increasing the roof R-value, which in this case R-49 and R-60 are the assumed retrofit targets. Different materials considered for improvement of wall R-value include blown-in cellulose, closed cell, and open cell spray foam. In the first scenario, R-11 and R-22 cellulose will be added to the existing insulation, while other scenarios will replace the whole existing insulation with spray foam insulation. Figure 3 shows the results of the analysis, where Points 1 through 6 correspond to R-49 & R-60 cellulose, R-49 & R-60 closed cell spray foam, and R-49 & R-60 open cell spray foam. It can be observed that the change in energy consumption would be up to 1.3% between the benchmark house and other retrofit scenarios. Based on the initial cost estimation outputs, the difference between the benchmark house and the lowest cost (for cellulose) and the highest cost (for open cell spray foam) is $500 and $6,000, respectively. Table 7 presents the summary of the outputs and shows that compared with previous single retrofit methods, it has relatively higher impact in energy consumption.

Different roofing materials

The studied house is located in a cold climate region and the heating demand is higher than cooling; therefore, it was decided to use the same concept and model the material with higher solar radiation absorptivity to decrease the heating load; this is what we may consider a warm roof. The absorptivity of roofing material in benchmark house is 0.85 that is relatively high. Also white metal, dark asphalt shingles, and dark metal with absorptivity of 0.3, 0.92, and 0.9 are modeled, respectively. In Figure 4, Points 1, 2, and 3 correspond to dark asphalt, dark metal, and white metal, respectively. The initial cost difference between the minimum cost (dark asphalt) and maximum cost (white/dark metal) is about $1,200. Table 7 shows the summary of the energy modeling results for different roofing materials. Again, it can be noticed that the energy saving percentage is low.

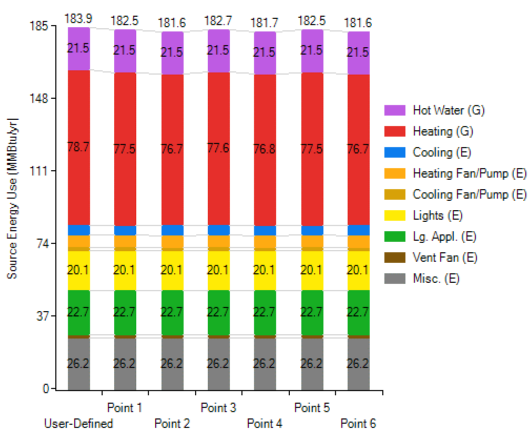

Figure 3. Comparison between energy consumption of different roof insulation

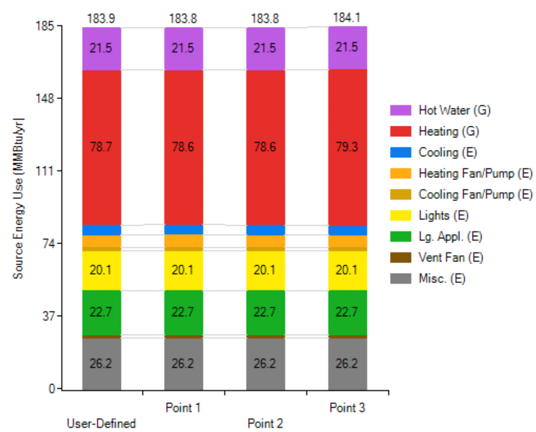

Figure 4. Comparison between energy consumption of different roof material with different solar radiation absorptivity

Adding slab insulation

There is no option in BEopt to add insulation for floor slabs. In this study, a carpet was assumed (as additional insulation) to cover 100% of the floor area as opposed to the benchmark house that is assumed to have a carpet covering 80% of the floor area. Based on the available information in BEopt different scenarios to investigate the effect of this retrofit method include using R-10 and R-20 fiberglass batt with a cost of \$0.24, and \$0.48 per ft^2, respectively. Figure 5 shows the energy performance of two different retrofit scenarios, including adding R-10 (Point 1) and R-20 (Point 2) fiberglass batt to the slabs. The results show that there is no significant improvement in terms of energy consumption, and the source energy saving is less than 1%; however, it still leads to 2.3 MMBtu saving in annual energy needs for heating. Table 7 summarizes the outputs.

Application of PCM

The PCM application method investigated here is limited to using PCM plaster as a coating material over an existing wall sheathing such as drywall or PCM wallboards that has embedded PCM capsules. To model these options, BEopt has two options to model drywall impregnated with PCM or PCM application on drywalls and these options are available for exterior wall, partition wall, and ceiling that can be covered with either of these components. The floor area considered for the interior walls is assumed to be 2232 ft^2, which is based on the floor area for two stories. Figure 6 shows the energy consumption of the benchmark house and two other retrofit scenarios, a house with external wall, partition wall, and ceiling covered with PCM drywall (Point1) and one with PCM coated drywall (Point 8). The results show that both scenarios can lead to lower energy consumption up to 4 MMBtu/year. However, the cost estimate outputs shows that the difference in initial construction costs between the benchmark house and two retrofit scenarios for points 1 and 8 are about \$55,200 and \$13,300, respectively, which are much higher construction cost compared with the benchmark house that is about \$59,000. Table 7 also presents a summary of the results.

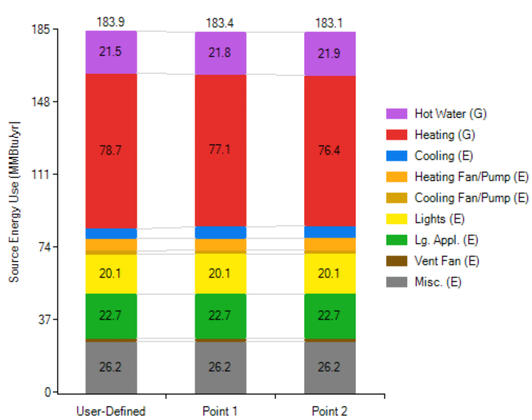

Figure 5. Comparison between energy consumption of different slab retrofit scenarios

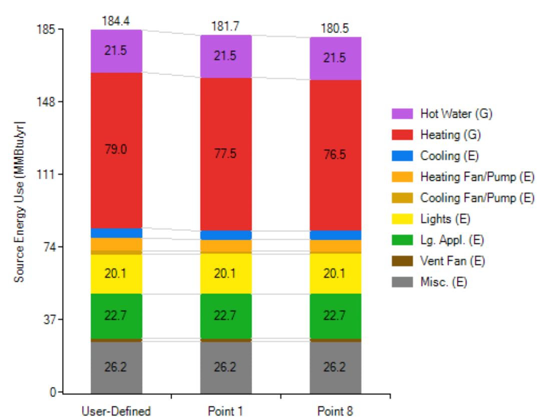

Figure 6. Comparison between energy consumption for two different scenarios of using PCM drywall and PCM coated drywall

Application of aerogel

The next method is application of layers of aerogel over walls, floors, and ceilings or adding panels containing aerogel. Based on two recent studies (Filate , 2014 & Casini, 2014), it was decided to define aerogel with thermal conductivity of 0.016

W/(m.K), which means an inch (2.54 cm) of aerogel would be equivalent to an R-value of about R-10. Also, it was assumed that the retrofit would include adding extra R-10 (1 inch of aerogel) to the walls and floors. The approximate cost of 10-mm thick aerogel blanket is $5.5/ft^2, which means that for an inch of aerogel, it will be about $14/ft^2 (http://www.buyaerogel.com/ & Shukla et al., 2011). The benchmark already has 80% coverage of R-2.1 carpet; therefore, a new layer of R-11.7 was defined for floors (80%×2.1 + 100%×10 = 11.7). While the labor cost for installing carpet is considered to be zero in BEopt, in this study, a labor cost of $0.5/ft^2 was considered in obtaining the total costs. Another scenario consisting of adding R-5 XPS as exterior insulation was also considered. As it can be observed in Figure 7, points 3 and 6 that correspond to walls with aerogel and floors without and with aerogel, respectively, show the minimum annual energy consumption compared to all other cases. The initial cost difference for these two new scenarios compared with the benchmark house is about $31,200 and $63,600, respectively. Although both scenarios lead to high energy saving (10.8% and 11.3%, respectively), the first scenario is relatively more economical with 52% increase in initial cost compared with the second scenario that leads to 108% increase in construction cost. As noted earlier, retrofitting of floors does not improve the energy performance significantly. Table 7 summarizes the results.

Decreasing air leakage

In this method, the difference in initial cost also includes the difference in HVAC sizing. Table 7 shows the properties of different scenarios considered for this retrofit method and it can be observed that despite the negligible difference in initial cost, the saving in source energy consumption can be up to 8.0% if the air leakage is decreased to 2 ACH50 from 7 ACH50. Table 7 also shows that point 2 (2 ACH50) leads to about 65 MMBtu/Year heating load.

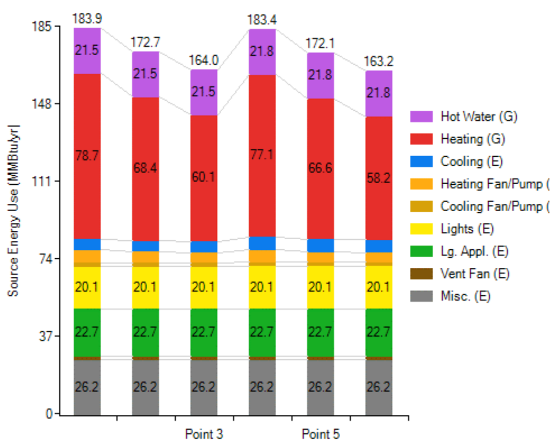

Figure 7. Comparison between energy consumption for different scenarios of using aerogel in floors/walls

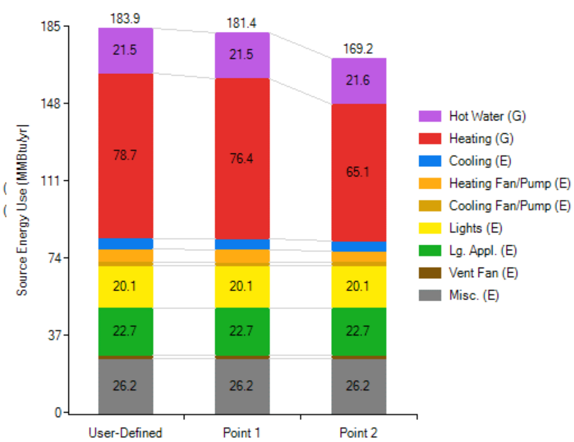

Figure 8. Comparison between energy consumption for different scenarios of air leakage

Summary of BEopt modeling and analysis results

Table 7 summarizes the source energy saving and construction cost of different single energy retrofit methods. It can be observed that single energy retrofit methods listed below can lead up to 11.3% or 10.8% source energy saving. However, the difference in initial cost is about $31,200 or $63,600, which is about 52% or 107% higher than the benchmark house, respectively. These two scenarios correspond to the application of aerogel in walls or floors, while there are other options such as adding exterior insulation that can save source energy by about 10.8% and keep the initial cost difference to about $3,200, which is only about 5.4% higher than the benchmark house. It is also observed that for cold climate regions such as Pennsylvania that heating seasons are dominant in terms of energy consumption, retrofit measures such as low SHGC windows, overhang, and white roof have negative impact on the annual energy consumption. Results about effectiveness of aerogel also show that walls that are retrofitted with aerogel have much higher impact on energy saving compared with floors.

Table 7. Summary of modeling different retrofit methods

Retrofit measure			Initial cost difference*	Source Energy Saving (normalized)**
Exterior insulation				
R-5 XPS			$1,200	6.1%
R-10 XPS			$2,200	9.0%
R-15 XPS			$3,200	10.8%
R-6 Polyiso			$1,000	6.8%
R-12 Polyiso			$1,800	9.8%
Window SHGC				
0.53 (High)			$-180	0.1%
0.30 (Low)			$-120	-0.5%
Roof Insulation				
R-49, Cellulose			$500	0.8%
R-60, Cellulose			$1000	1.3%
R-49, Closed cell spray			$3,700	0.7%
R-60, Closed cell spray			$4,800	1.2%
R-49, Open cell spray			$4,900	0.8%
R-60, Open cell spray			$6,000	1.3%
Roofing materials	Color	Absorptivity		
Asphalt Shingles	Dark	0.92	$0	0.0%
Metal	Dark	0.9	$1,200	0.02%
Metal	White	0.3	$1,200	-0.14%
Slab retrofit				
R-10 Fiberglass batt			$1,500	0.3%
R-20 Fiberglass batt			$2,100	0.4%
PCM application				
PCM Drywall			$55,200	1.5%
PCM coated Drywall			$13,300	2.1%
Air leakage				
5 ACH50			$130	1.3%
2 ACH50			$270	8.0%
Aerogel in wall	Aerogel in floor	XPS in wall		
-	-	✓	$1,200	6.1%

✓	-	✓	$31,200	10.8%
-	✓	-	$32,300	0.3%
-	✓	✓	$33,600	6.4%
✓	✓	✓	$63,600	11.3%

* Difference is calculated from the initial cost of the benchmark house that is $59,000.
** Negative sign shows increase in energy consumption compared with benchmark house.

Effect of climates

In order to investigate the effect of different single retrofit methods in various climates it was decided to do the analysis in two more locations including Boston, Massachusetts and Arlington, Virginia. Table 8 shows the annual energy consumed in each location. Figure 9 shows a few selected single retrofit methods that have higher impact on energy saving and the vertical axis shows the maximum annual energy saving on heating loads for different method in Million Btu compared with the benchmark house. It shows that using aerogel on exterior walls, exterior insulation, and reduction in air leakage lead to high reduction in heating loads and this value is larger in colder regions. Using PCM shows higher impact in relatively warmer regions however, it is not significant. Roof insulation, slab retrofit, and adding window film show a better performance in relatively colder regions.

Table 8. Annual energy consumption of benchmark house in different locations

Location	Annual Energy Consumption (MMBtu)
Boston, MA	79.7
Pittsburgh, PA	78.7
Arlington, VA	51

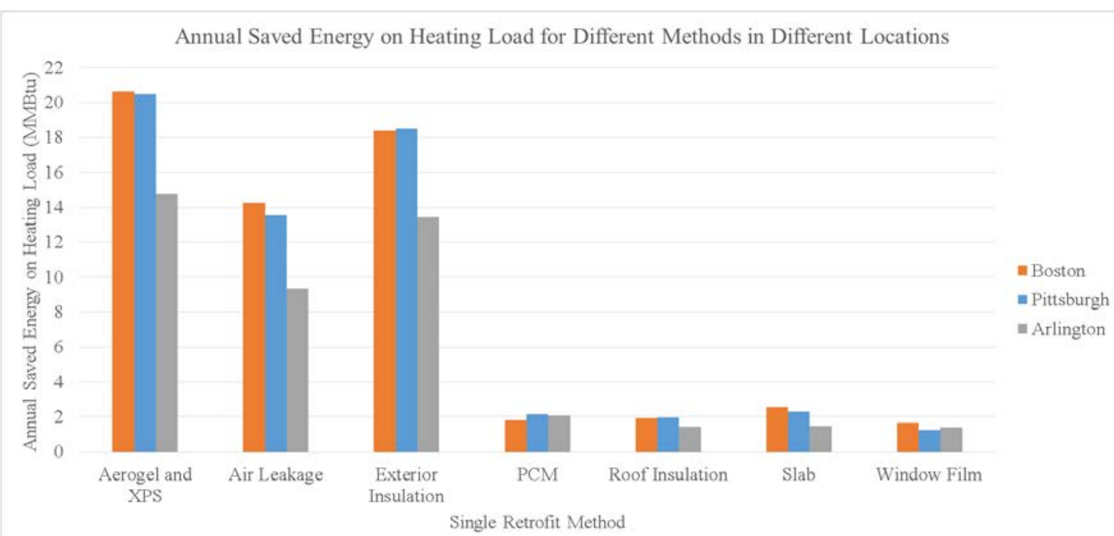

Figure 9. Annual saved energy on heating load for different single energy retrofit methods compared with benchmark house

Summary and Conclusions

Among different sectors that contribute to total annual energy consumption in the U.S., residential construction has 22% share. About 42% of this energy use is considered resulting from heating and cooling, while about 36% is due to heat loss and gain during heating and cooling season, respectively.

In order to study the effectiveness of several single energy retrofit options, computer models were developed using BEopt software package, which helped compare the total cost (including construction and energy related cost) and source energy saving percentage against a benchmark house. To define the properties of the benchmark house, the predefined benchmark house in BEopt was edited based on the census data for residential buildings in the U.S. between 1990 and 2000. Results show that single retrofit measures studied in this report can reduce the total source energy saving up to 11.3% such as using aerogel in walls and floors, however it can increase the construction cost up to 63%. On the other hand, application of R-15 XPS can lead to 10.8% source energy saving and limit the increase in construction cost to only 2.3% compared with benchmark house. There are also other methods that can improve the energy consumption up to 8.1% including decreasing the air leakage to 2 ACH50 from 7 ACH50. It also limits the increase in total cost to about $270 that is only about 0.33% increase in initial cost. Moreover, the results show that using certain retrofit measures can lead to increase in energy use such as windows with lower SHGC, and white roofing material. This can be understood by considering the climate region that the house is modeled for. In cold climate regions such as Pennsylvania, it is more important to have higher solar heat gain rather than preventing the solar radiation absorption because the heating season is the dominant one in terms of energy consumption. Other retrofit measures such as using PCM in different components as coating or encapsulation within sheathing materials can lead to 2.1% and 1.5% energy saving, respectively. Initial cost with respect to the benchmark house, however, can increase up to 20% and 90%, respectively. The highest impacts are related to adding exterior insulation, roof insulation, reducing air leakage, using aerogel and PCM; the first one is the most economical option specially compared with using aerogel and PCM. The results of the simulation study would depend on the properties of the house under study. In order to find the impact of these retrofit methods for other existing houses, appropriate computer modeling would be required. It should also be noted that other retrofit measures such as improving mechanical and electrical components can have significant impact in energy saving of residential buildings. Such retrofit options, however, were not within the scope of the present study.

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